

Contents

1	Introduction to Carbon	1
	References	4
2	Carbon Nanotubes	7
2.1	History of Carbon Nanotubes	8
2.1.1	History Before 1991	8
2.1.2	History Since 1991	10
2.1.3	History of Aligned Carbon Nanotubes	11
2.2	Structures of Carbon Nanotubes	16
2.2.1	Graphite	16
2.2.2	Single-Walled Carbon Nanotubes	17
2.2.3	Double-Walled Carbon Nanotubes	18
2.2.4	Multi-Walled Carbon Nanotubes	19
2.2.5	Bamboo-Like Carbon Nanotubes	19
2.2.6	CNT Y-Junctions	20
2.2.7	Carbon Nanobuds	21
2.2.8	CNT Nanotorus and Micro-Rings	23
2.2.9	Carbon Microtubes	24
2.2.10	Amorphous Carbon Nanotubes	25
2.2.11	Coiled Carbon Nanotubes	26
2.2.12	Flattened Carbon Nanotubes	26
2.2.13	Other Carbon Nanomaterials	28
2.3	Physical Properties of Carbon Nanotubes	30
2.3.1	Anisotropic Mechanical Properties	30
2.3.2	Anisotropic Electrical Properties	30
2.3.3	Anisotropic Thermal Conductivity	31
2.3.4	Anisotropic Thermal Diffusivity	32
2.3.5	Anisotropic Seebeck Coefficient	34
2.3.6	Other Anisotropic Physical Properties	34
	References	35

3	Growth Techniques of Carbon Nanotubes	45
3.1	Arc Discharge	45
3.2	Laser Ablation	47
3.3	Chemical Vapor Deposition	48
3.4	Hydrothermal Methods	52
3.5	Flame Method	56
3.6	Disproportionation of Carbon Monoxide	57
3.7	Catalytic Pyrolysis of Hydrocarbons	59
3.8	Electrolysis	59
3.9	Solar Energy	60
	References	61
4	Chemical Vapor Deposition of Carbon Nanotubes	67
4.1	Thermal Chemical Vapor Deposition	67
4.1.1	Hot-Wall Chemical Vapor Deposition	68
4.1.2	Hot-Wire Chemical Vapor Deposition	70
4.1.3	Thermal Chemical Vapor Deposition Growth Mechanism of Carbon Nanotubes	71
4.1.4	Experimental Condition of Carbon Nanotube Array Growth	73
4.2	Plasma-Enhanced Chemical Vapor Deposition	75
4.2.1	Direct Current Plasma-Enhanced Chemical Vapor Deposition	76
4.2.2	Radio-Frequency Plasma-Enhanced Chemical Vapor Deposition	78
4.2.3	Microwave Plasma-Assisted Chemical Vapor Deposition	78
4.2.4	Plasma-Enhanced Chemical Vapor Deposition Growth Mechanism of Carbon Nanotube Alignment	80
4.2.5	Experimental Conditions of Plasma-Enhanced Chemical Vapor Deposition Growth	83
	References	86
5	Physics of Direct Current Plasma-Enhanced Chemical Vapor Deposition	93
5.1	Equipment Setup and Growth Procedure	93
5.2	Substrate and Underlayer	95
5.3	Growth Temperature	96
5.4	Plasma Heating and Etching Effects	97
5.5	Plasma States	99
5.6	Catalyst Crystal Orientation	100
5.7	Electric Field Manipulation	101
5.8	DC-PECVD Growth Mechanism	102
5.8.1	First Stage: Randomly Entangled CNT Growth	102

5.8.2	Second Stage: Partially Aligned CNT Growth	104
5.8.3	Third Stage: Fully Aligned CNT Growth	105
5.8.4	DC-PECVD Growth Mechanism	106
	References	107
6	Technologies to Achieve Carbon Nanotube Alignment	111
6.1	In Situ Techniques for Carbon Nanotube Alignment	112
6.1.1	Thermal Chemical Vapor Deposition with Crowding Effect.	112
6.1.2	Thermal Chemical Vapor Deposition Growth with Imposed Electric Field	116
6.1.3	Thermal Chemical Vapor Deposition Growth Under Gas Flow Fields	119
6.1.4	Thermal Chemical Vapor Deposition Growth with Epitaxy	123
6.1.5	Thermal Chemical Vapor Deposition Under Magnetic Fields.	128
6.1.6	Vertically Aligned Carbon Nanotube Arrays Grown by Plasma-Enhanced Chemical Vapor Deposition	128
6.1.7	Other In Situ techniques.	140
6.2	Ex Situ Techniques for Carbon Nanotube Alignment.	140
6.2.1	Ex Situ Alignment Under Electric Fields	141
6.2.2	Ex Situ Alignment Under Magnetic Fields	141
6.2.3	Ex Situ Mechanical Methods	143
6.2.4	Other Ex Situ Methods.	147
	References	147
7	Measurement Techniques of Aligned Carbon Nanotubes	157
7.1	Scanning Electron Microscopy	157
7.2	Bragg Diffraction	160
7.2.1	X-Ray Diffraction	160
7.2.2	Neutron Diffraction	164
7.2.3	Electron Diffraction	164
7.2.4	Light Diffraction	166
7.3	Small-Angle Scattering.	168
7.3.1	Small-Angle X-Ray Scattering	168
7.3.2	Small-Angle Neutron Scattering	172
7.4	Raman Spectroscopy	173
7.5	Transmission Electron Microscopy	176
7.6	Scanning Tunneling Microscopy	178
7.7	Atomic Force Microscopy	179
7.8	Other Techniques	179
	References	180

8 Properties and Applications of Aligned Carbon

Nanotube Arrays	183
8.1 Field Emission Devices	183
8.1.1 Field Emission of Aligned Carbon Nanotube Arrays . . .	184
8.1.2 Carbon Nanotube Array Emitters.	187
8.1.3 High-Intensity Electron Sources	188
8.1.4 Lighting	189
8.1.5 Field Emission Flat Panel Displays	191
8.1.6 Incandescent Displays	193
8.1.7 X-Ray Generators	194
8.1.8 Microwave Devices	195
8.1.9 Other Field Emission Devices	197
8.2 Optical Devices	198
8.2.1 Photonic Crystals.	198
8.2.2 Optical Antennae.	199
8.2.3 Optical Waveguides	202
8.2.4 SWCNT Array Solar Cells	204
8.2.5 Solar Cells Based on MWCNT Nanocoaxes	204
8.3 Nanoelectrode-Based Sensors	208
8.3.1 Nanoelectrode Arrays.	208
8.3.2 Ion Sensors.	213
8.3.3 Gas Sensors	215
8.3.4 Biosensors	222
8.4 Thermal Devices: Thermal Interface Materials	228
8.5 Electrical Interconnects and Vias.	231
8.6 Templates.	235
8.7 Aligned-CNT Composites and Applications	236
References	236

9 Potential Applications of Carbon Nanotube Arrays 255

9.1 Mechanical Devices	255
9.1.1 Carbon Nanotube Ropes	256
9.1.2 TEM Grids	259
9.1.3 Artificial Setae	260
9.1.4 Piezoresistive Effects: Pressure and Strain Sensors	260
9.2 Electrical Devices	263
9.2.1 Random Access Memory	263
9.2.2 Low κ Dielectrics	264
9.2.3 Transistors	265
9.3 Acoustic Sensors	265
9.3.1 Artificial Ears	265
9.3.2 Thermoacoustic Loudspeakers.	265
9.4 Electrochemical and Chemical Storage Devices	269
9.4.1 Fuel Cells.	270

9.4.2	Supercapacitors	274
9.4.3	Lithium Ion Batteries	279
9.4.4	Hydrogen Storage	280
9.5	Electromechanical Devices: Actuators	280
9.6	Terahertz Sources	281
9.7	Other Applications.	282
	References	283
Epilogue		291
Index		293